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May 16, 1974

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NIC No. 30582
Packet Radio Temporary Note No. 102

MULTIPLE CHANNEL PACKET RADIO NETWORKS

Abstract: Theoretical maximum throughput rates are found for a number of different multi-repeater networks by choosing an optimum division of the original single channel into multiple channels.

The DAMN FINE (Dynamically Allocated Multiple-channel Network For Improved Network Efficiency) concept has been described in PRTN #82. An arbitrary network with one station, four repeaters and 30 terminals has been chosen for comparing the DAMN FINE concept with carrier sense and Aloha packet switching concepts. The DAMN FINE system could give a throughput of 0.28 to 0.30 compared to 0.20 for carrier sense, 0.19 unslotted Aloha and 0.26 for slotted Aloha. Another multiple channel configuration of this network (probably not realizable with DAMN FINE control) has a throughput of 0.54. All of these throughputs are for a fixed average delay.

There is a discussion of the busy tone access mode, an alternative solution to increasing throughput in multi-repeater networks.

RECEIVED AT NIC MAY 17, 1974.

I Introduction

The division of a channel into two separate channels with equal capacity has been investigated in PRTN 45. This analysis was for a single station, no repeater network in which one channel was used for messages from terminals to the station (up traffic) and the other channel was used for messages from the station to the terminals (down traffic). It was found that when the ratio of up traffic to down traffic was in a certain range, dividing the original channel into two equal capacity channels increased the system throughput. However, when the ratio of up to down traffic was outside this range better performance was obtained with a single channel. These results imply that for a fixed ratio of up to down traffic a two-channel system, with optimal channel division, is better than a single channel system. If the ratio of up to down traffic varies widely, either a single channel should be used or a dynamic channel division scheme should be developed.

The DAMN FINE Concept (PRTN 82) utilizes multiple channels which are dynamically allocated. Channels are selected locally based on the sensed traffic load. As originally configured, terminals can operate on only one channel at a time and repeaters can only operate on two channels at a time (one, the outbound channel, will carry traffic to and from repeaters farther from the station and to and from local area terminals; and the second, the inbound channel, will carry traffic to and from the repeaters next on the route to the station). All channels would be equal in information capacity.

The purpose of this note is twofold: first to examine the maximum throughput, without concern for average delay, that can be obtained with multiple channels in networks containing several repeaters, and second, to investigate the maximum throughput for a fixed average delay that can be obtained with the DAMN FINE concept. Throughput, as used in this note, is the total information flowing in and out of the network divided by the information capacity of the total system bandwidth.

II Performance of Idealized Multiple Channel Networks

In this section several assumptions are made which make the analysis easier and allow an upper bound to be found for throughput:

- Terminals are located in groups called terminal areas. Each terminal can hear every other terminal in its terminal area, but cannot hear any terminal outside the terminal area. With each terminal area there is an associated repeater or station which can hear every terminal in the terminal area. Terminals can hear only the repeater or station associated with their terminal area.
- Each terminal area generates packets at an equal rate. These packets are destined for the station. For each packet received, the station returns r packets (r need not be an integer).

- A carrier sense access mode is used. Detection and propagation delays are nil.
- Bandwidth used for an acknowledgement scheme is ignored.
- The components of the system either have sufficient storage or generate packets rapidly enough to keep the system filled to capacity. I.e., if the system consisted of only a station and terminals (none hidden) the maximum throughput would approach unity.

Under these assumptions, it is not difficult to investigate the throughput of a number of different network configurations. Figure 1 shows a network that was examined. There is a station and four repeaters. There are six terminals associated directly with the station and six terminals associated with each of the repeaters. The terminals can hear other terminals in their terminal area and their associated repeater or station. They cannot hear any other components in the system. All repeaters can hear each other. The two upper repeaters and the station can hear each other. Figure 2 outlines a proof that the maximum throughput of this network is 5/7 or 0.714. Note that for this particular network the maximum throughput is independent of the ratio of up traffic to down traffic.

Figure 3 illustrates one-way maximum throughputs for a series of N repeaters in a line with the station at the end of the line. Adjacent repeaters or stations can hear each other, but cannot hear the second repeater (or station) down the line. As before, terminals can hear only terminals in their own area

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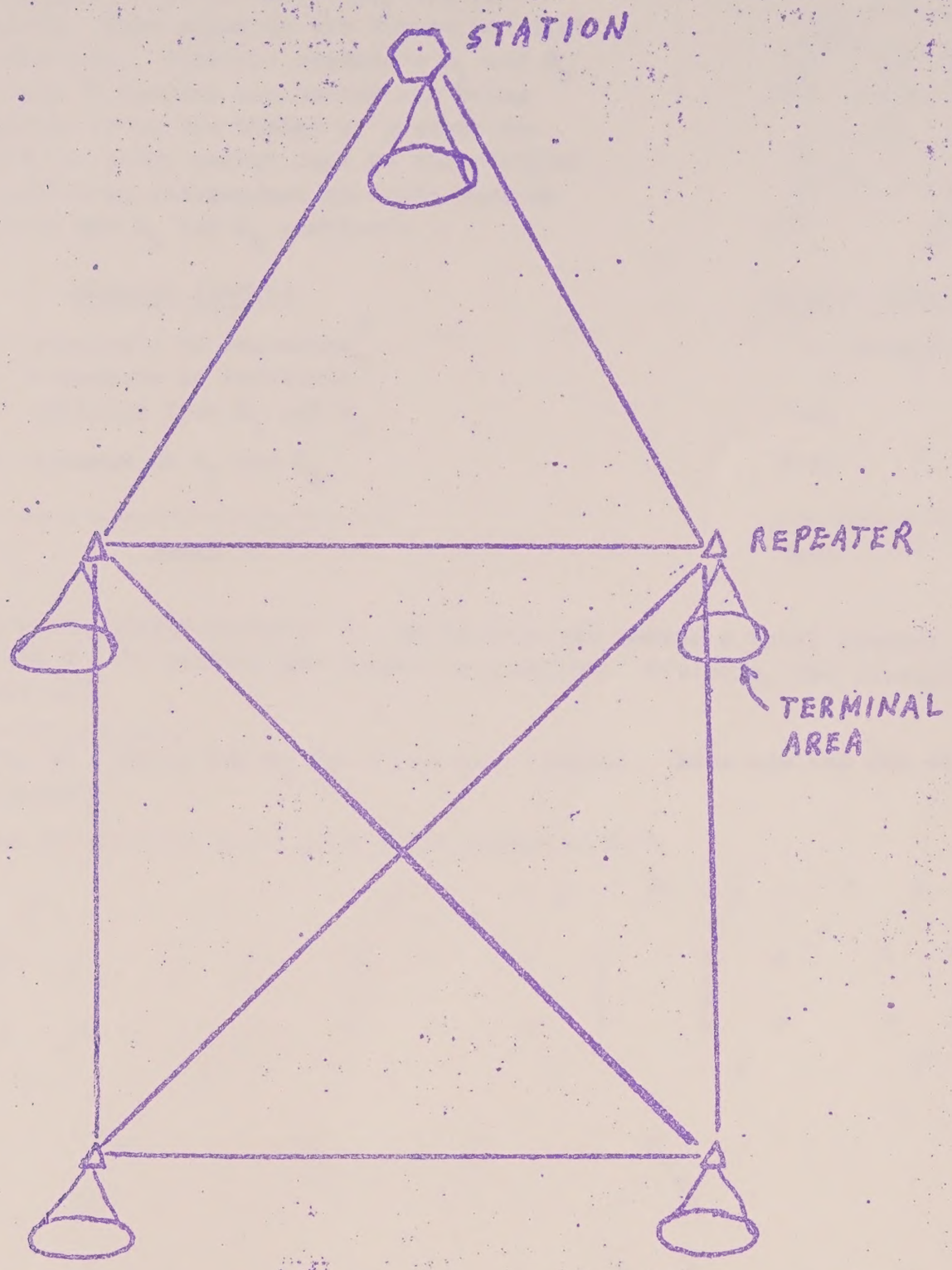
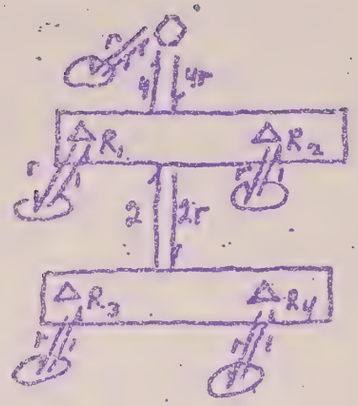


Figure 1 A Multi-Repeater Network that was examined. A line between repeaters or stations means that they can hear each other.

I. Minimum required information flow:

From Figure 1 it is clear that the information flows shown in the figure at right are required. Consider repeaters R_1 and R_2 when 5 + 5r packets per second are being generated (r is the number of packets returned for every packet sent to the station). The following independent channels must be supplied for R_1 and R_2 combined:

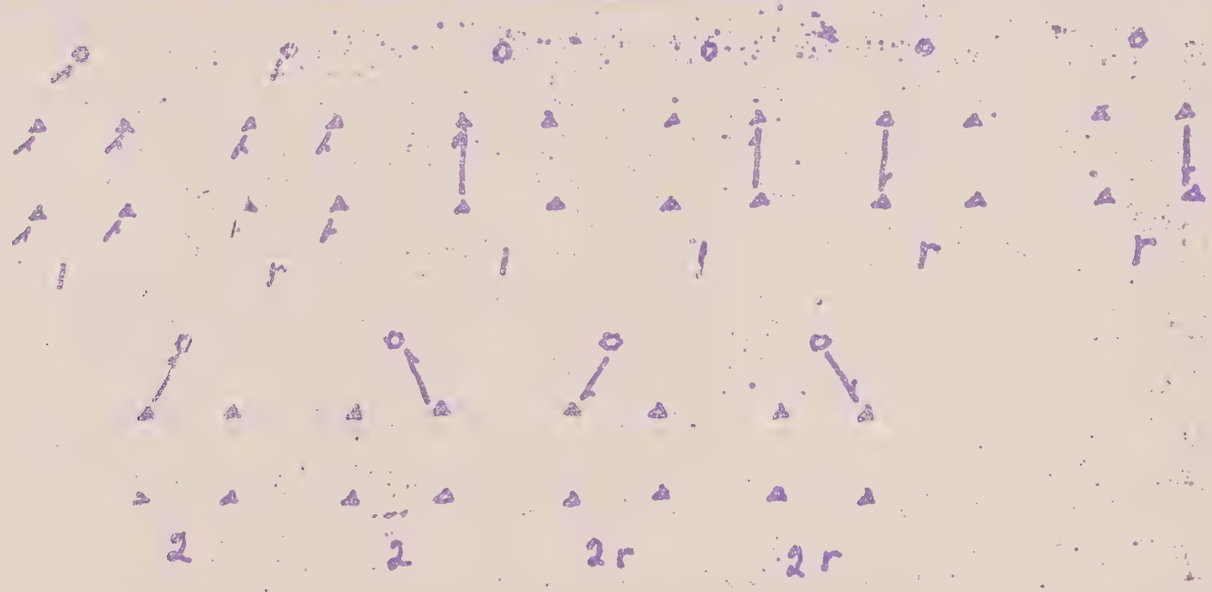


Channel traffic		Channel Capacity
1)	terminals to repeaters*	1 packet/sec
2)	repeaters to terminals*	r "
3)	outbound from R_1 and R_2	4+2r "
4)	inbound to R_1 and R_2	2+4r "
	Total	7+7r "

Thus, to successfully transmit 5 + 5r packets per second a total channel capacity of at least 7 + 7r packets per second is required. Dividing, the throughput must be at most 5/7.

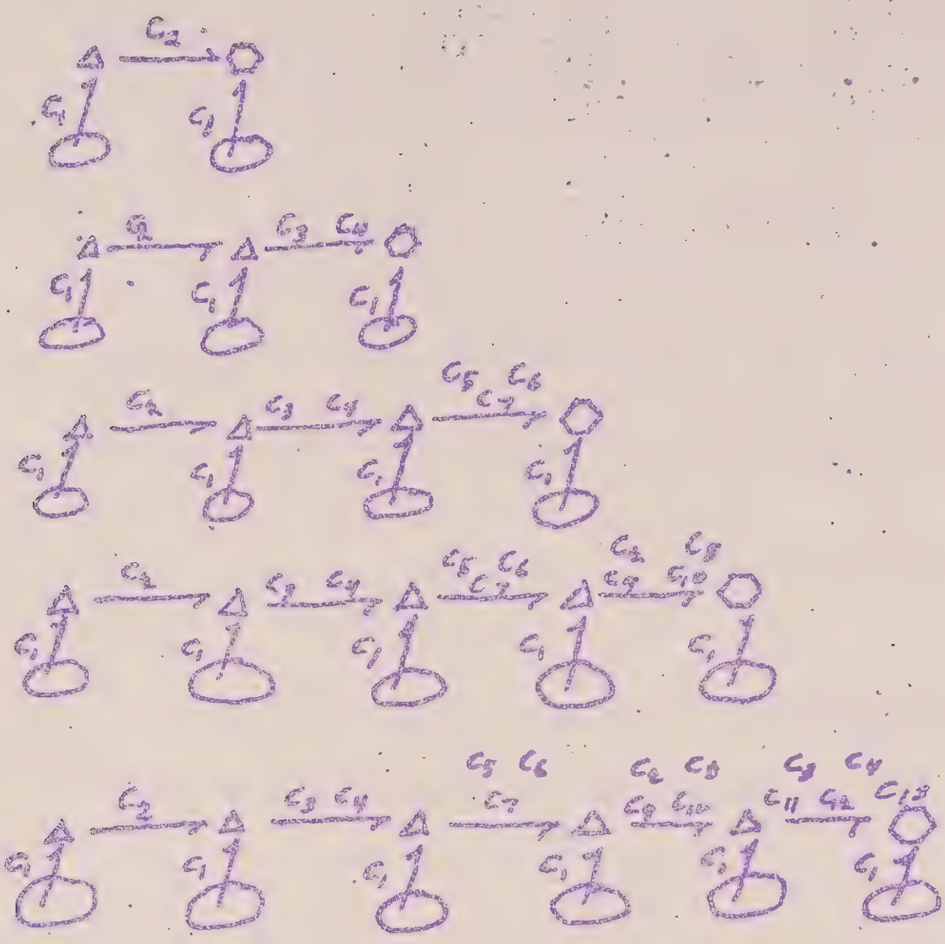
* Traffic to both R_1 and R_2 can be on same channel. Same applies for traffic to terminals.

II. A set of channels which give a throughput of 5/7.



The numbers below each figure are channel capacity in packets per second. 5 + 5r packets per second are successfully transmitted in 7 + 7r total channel capacity.

Figure 2 Outline of proof for maximum information capacity of a network.



Number of Repeaters (N)	Number of Channels *	Throughput
1	2	1
2	4	3/4
3	7	4/7
4	10	1/2
5	13	6/13
10	28	11/28
100	298	101/298
N	(3N-2)	$\frac{N+1}{3N-2}$
∞		1/3

Terminal area
Repeater
Station

* All channels are of equal capacity

Figure 3 Throughput of a line of repeaters with a station at one end. Only adjacent repeaters (station) can hear each other. The figure shows how the channels are arranged. All channels in a given configuration have equal information capacity. Note that for N ≥ 4, channel(s) can be used over again further down the line.

and the repeater (or station) associated with their area. The maximum throughput values, in general, only apply to one-way transmissions (either from the terminals to the station or from the station to the terminals). For some values of N it is possible to obtain higher maximum throughputs depending on the ratio of up to down traffic.

Figure 4 gives throughputs of several other network configurations under the assumptions listed above. It is surprising to note the number of configurations in which a maximum throughput of unity can be obtained.

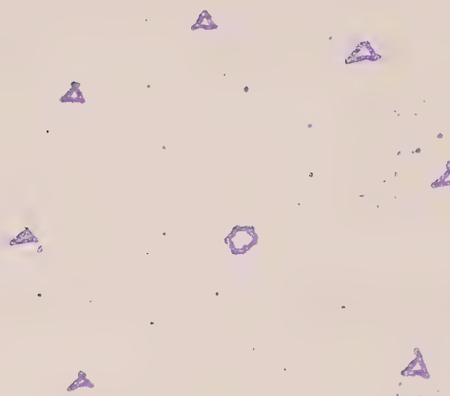
III Performance with DAMN FINE

Evaluating the performance of the DAMN FINE concept presents two problems. First is the problem of examining the DAMN FINE control algorithm to find the range of multichannel networks it can configure. Second is the problem of finding throughput and delays for a multichannel network with carrier sense and some hidden components. The first problem has not been investigated. Rather, a number of channel configurations have been chosen.

The network geometry chosen for investigating DAMN FINE concept is illustrated in Figure 1. This network was chosen because performance data for various access modes is available. This data was obtained from a simulation (PRTN 81, and more details will be published in a future PRTN). The simulation was run with six terminals in each terminal area, for a total of 30 terminals in the system. All packets from the terminals are destined for the station. For every packet arriving at the station, two packets are returned to the originating terminal. Additional network assumptions:

Hearability: Repeaters and Station can hear each other provided they are no more than $\sqrt{2}$ distance units apart.

Throughput: 17/21 for one-way traffic



Hearability: Repeaters can hear only their nearest neighbor and the station. The station can hear all repeaters.

Throughput: 1 for any ratio of up and down traffic and any number of repeaters.

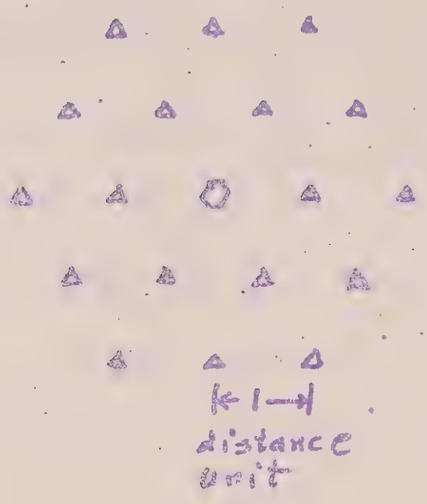
Hearability: Defined by connecting lines.

Throughput: 1 for any ratio of up and down traffic

Figure 4 Maximum throughputs for several miscellaneous networks. There is a terminal area associated with each repeater and station (not illustrated). The terminals can hear, and be heard by, only their associated repeater or station.

Hearability: Station and repeaters can hear only their nearest neighbor.

Throughput: 1 for any ratio of up and down traffic and for any number of repeaters.



Hearability: Station and repeaters can hear each other if they are 1 distance unit away.

Throughput: 1 for any ratio of up and down traffic.

Station ⬡ Repeater △

Figure 4 (continued)

- The terminal transmit buffer holds only a single packet. The station and repeaters have unlimited buffer capacity.
- Given that the terminal buffer is empty, the arrival time of the next packet is exponentially distributed.
- For the carrier sense access mode, conflicts can occur if two components sense within .01 of the packet transmission time of each other due to propagation and detection delays.
- There is $\frac{a}{A}$ separate 100% reliable acknowledgement system requiring 1/10 of a packet transmission time to complete an acknowledgement. (For the multi-repeater network this is a hop by hop acknowledgement.)

The first channel configuration (see Figure 5) chosen for investigation conforms to the original DAMN FINN concept. Namely, all channels have equal information capacity, all channels carry both up and down traffic, repeaters use one channel for communications with terminals and repeaters located further away from the station and a second channel for communications with the station or repeaters closer to the station (i.e., terminals may only operate on one channel at one time, and repeaters may only operate on two channels at one time). In Figure 5 the uncircled numbers represent the information that flows over each link when one packet is generated at (or sent to) each of the five terminal areas. The circled numbers are average terminal to station to terminal delays in units of packet transmission times (referred to the new divided channels). The throughput and delay for each of the channels can be analyzed separately.

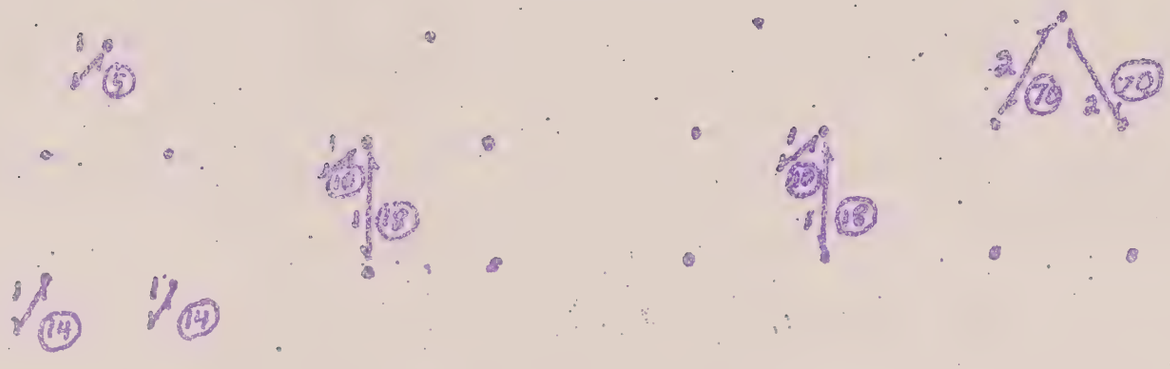


Figure 5 The Original DAMN FINE Concept Channel Configuration. Each graph represents one channel.

The delay times correspond to those associated with a "throughput" of 0.22 packets per terminal area per transmission time. These results were obtained from simulations of a single station ten terminal network (both for terminals with a single packet buffer and for terminals with unlimited buffers) and will be reported in a future PRAN. To equate this throughput

to other throughputs given in this note, it must be multiplied by 5 (the number of terminal areas) and then by 1/4 (the individual channels have only 1/4 of the capacity of the original undivided channel) to obtain a throughput of 0.28. This result may be slightly pessimistic because there are fewer components involved than in the network examined in the simulation.

The delay time is found by summing the delays for each link of the system packets must traverse. The delay is averaged over the five terminal areas:

$$\frac{1}{5} \times 5 + \frac{2}{5} \times (70 + 10) + \frac{2}{5} (70 + 18 + 14) \approx 75$$

packet transmission times on one of the divided channels. It takes four times as long to transmit a packet on a divided channel as compared to the original undivided channel. Thus, referred to the original undivided channel, average delay is 300 packet transmission times.

The second network configuration examined involves a departure from the original DAMN FINE concept. Repeaters are allowed to use two channels for communications with the station or the next repeater towards the station, one channel for communications with the next repeater in the direction away from the station, and one channel for communications with the terminals. In other words, a repeater may use up to four channels rather than being limited to two channels as in the original DAMN FINE concept. As before,

all channels carry both up and down traffic.. The network, shown in Figure 6, has a total of ten equal capacity channels of which two pairs are operated in parallel along single links which carry heavy traffic.

An analysis similar to that for the configuration with four channels yields a throughput of 0.30 with an average delay of 300 packet transmission times (where packet transmission time is defined as the length of time to transmit a packet on the original undivided channel).

The 21 channel configuration shown in Figure 7 can give even higher throughputs. This network departs even further from the original DAMN FINE concept in that all channels are used in only one direction. Using data from one-way carrier sense channels in PRTN 67 gives a throughput of 0.54 with an average delay of 300 packet transmission times (where packet transmission time is defined as the length of time to transmit a packet on the original undivided channel). It should be noted that there are some differences between the carrier sense mode used and the assumptions made in the above 4 and 10 channel networks and the one-way delay times presented in PRTN 67.

In order for the channel configuration in Figure 7 to be realized, appreciable changes would have to be made in the DAMN FINE control algorithm. This is especially true for the downlink channels from the repeaters to the

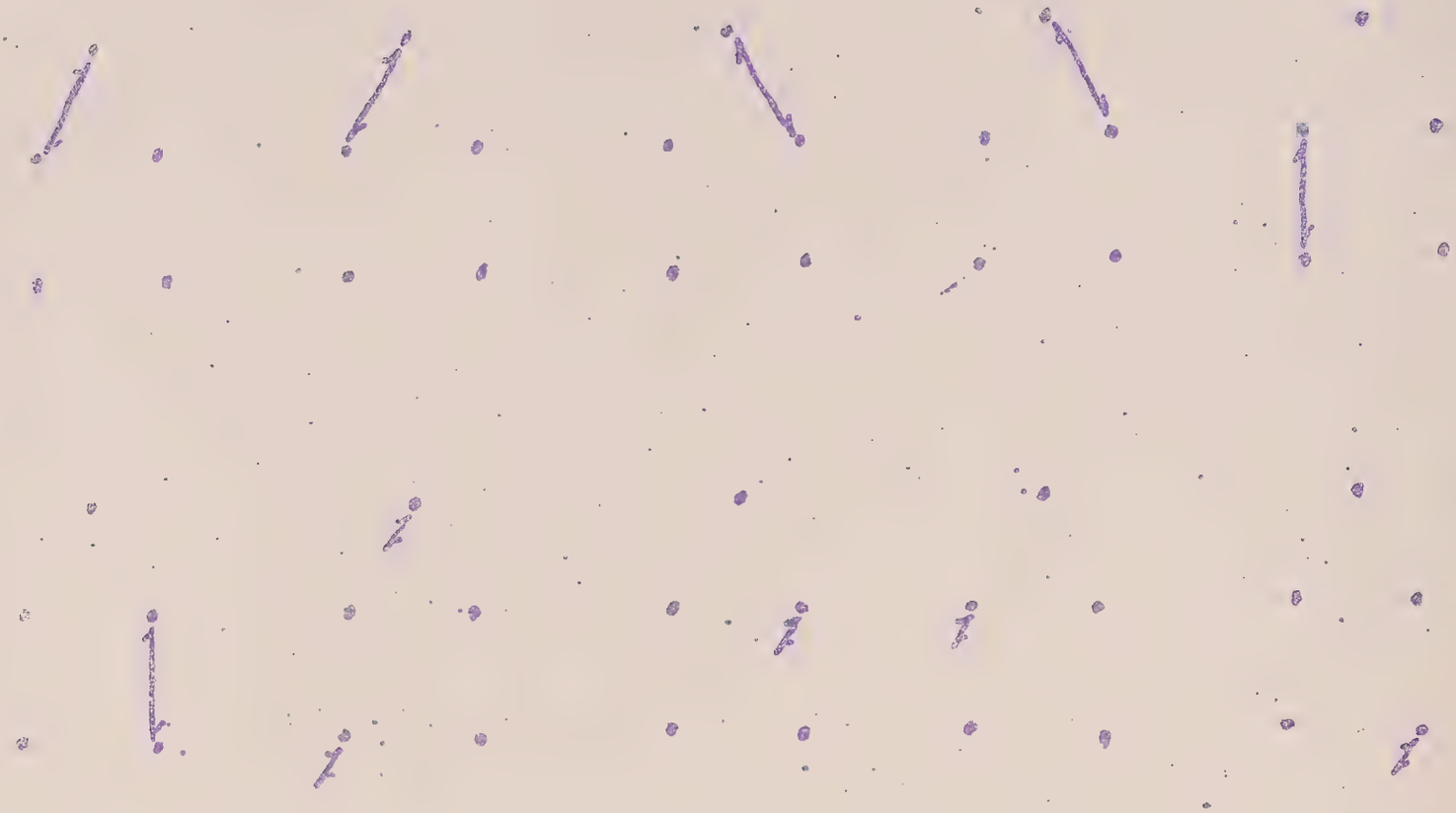


Figure 6 A Ten Channel Modified DAMN FINE Configuration.
Each graph represents one channel.

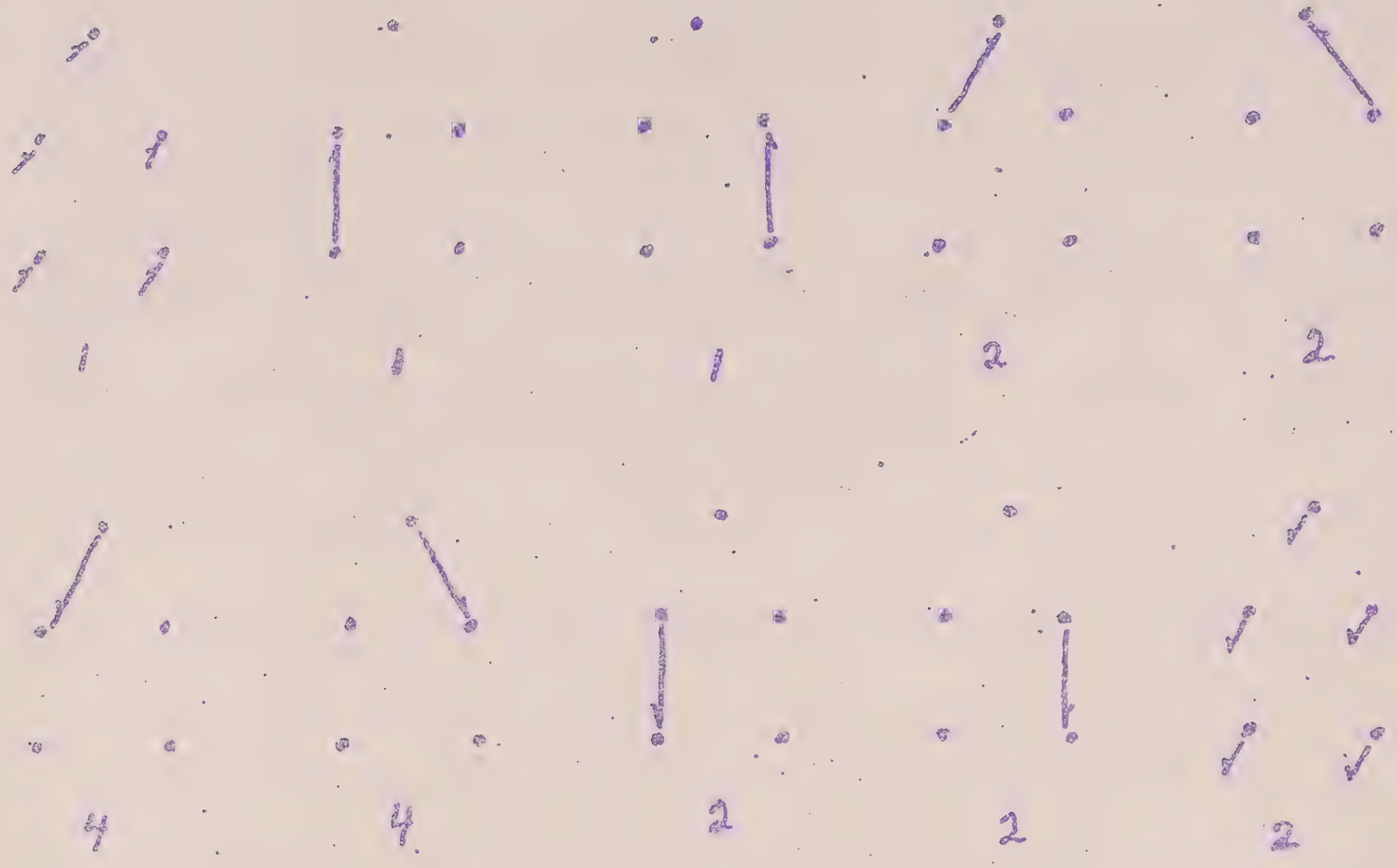


Figure 7 A 21 channel configuration. The numbers under each graph represent the use of multiple channels along a link(s). For every packet sent to the station two are returned to the terminals.

terminals. With DAMN FINE control the repeaters would hear each other and look for a channel with less traffic even though no interference will result from all repeaters and the station transmitting on the same frequency. In order for the configuration in Figure 7 to be realized, the control algorithm needs to have a knowledge of where simultaneous transmissions will not cause collisions.

Table 1 summarizes the performance of the various channel configurations of the four repeater network considered above. Also shown are the performances of single channel networks using unslotted Aloha, slotted Aloha and carrier sense access modes.

The maximum throughput of a network in a many channel configuration is generally higher than for the same network in a single channel configuration. However, at a low throughput rate the single channel configuration may have lower delay times, simply because the packet transmission time is less. Thus, in examining Table 1, it should be noted that the maximum throughputs of the different networks would show considerably more spread than do the throughputs with an average delay of 300 packet lengths.

Table 1 Throughputs of various access modes and channel configurations when terminal-station-terminal delay is 300 packet transmission times (referred to the original single channel).

Network Configuration	Throughput
Unslotted Aloha (single channel)	0.19*
Slotted Aloha (single channel)	0.26*
Carrier Sense (single channel)	0.20*
Original DAMN FINE (carrier sense, 4 channels)	0.28**
Modified DAMN FINE (carrier sense, 10 channels)	0.30**
21 one-way channels, carrier sense	0.54***

* Simulation results, to be reported in future TPRN

** Derived from simulation results, to be reported in future TPRN.

*** Derived from simulation results in TPRN 67

IV Discussion

The above examples are by no means an exhaustive study of the advantages and disadvantages of multiple channel networks. However, they do show that multiple channel configurations show a potential for large gains in throughput over single channel networks using Aloha or carrier sense access schemes.

As was shown in TPRN 45 , a fixed multi-channel configuration is not effective when loads change within the network. Changing loads from various parts of the network require adaptive control of the channels to insure that more channels are used along links with the highest traffic. A centrally controlled network would be a departure from the packet radio concept. The appeal of the DAMN FINE concept is that it employs a relatively simple control algorithm which operates locally; i.e., each component determines what channel it will use by listening to the surrounding environment. The disadvantage of the DAMN FINE concept, at least as shown in Table 1, is that it does not fully take advantage of the increase in throughput that can be realized with multiple channels. Further investigation of local control algorithms may lead to further increases in performance.

An alternate method of increasing throughput in a multi-repeater network would be to use a busy tone access mode. To date, this access mode has not been studied for multi-repeater networks, but it should eliminate the primary cause of reduced throughput in multi-repeater networks utilizing the carrier

sense access mode; hidden terminals/repeaters/station. For example, a terminal and a repeater, which cannot hear each other, simultaneously transmit to a station which can hear both the terminal and the repeater. To use the busy tone mode effectively in a multi-repcater network the previously proposed system (see PRTN 51) must be modified. This system was conceived for a network with only a station and terminals, with the busy tone broadcast only by the station. In a multi-repeater network it is necessary that the busy tone be played by every listening component, be it terminal, repeater or station. This insures that no other component that can be heard will interfere with the listening component. Channel effioiency could be increased even further by stopping any transmission that is not acknowledged by a busy tone after the packet header has been broadcast. Failure to receive a busy tone implies that the component which was addressed is transmitting and cannot receive; continued transmitting needlessly occupies the channel.